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Thermal-hydraulic analysis of the ITER CCWS-1 cooling loop

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ABSTRACT

ITER is designed to produce heat power from the deuterium-tritium fusion reaction burning the confined plasma inside the vacuum vessel. The effective removal of the power generated from fusion reactions and auxiliary systems (e.g. plasma heating systems, cryogenic systems, coils, etc.) represents a key point for the success of ITER. CCWS-1 is a pressurized cooling loop with the main function to guarantee cooling water to TCWS and other served auxiliary systems (e.g. vacuum pumps) maintaining temperature, pressure, flow rates and water chemistry within prescribed values. To support the CCWS-1 design and verify the requirements at the clients' interface during the different operational modes of the machine, a thermal-hydraulic campaign has been carried out. The work has been conducted using the commercially available thermal-hydraulic software AFT Fathom, performing steady-state and heat transfer analyses of complex systems. The present paper summarizes the computational models, and the hypotheses and critically discusses the obtained outcomes.

Abbreviations

CCWS	Component Cooling Water System
CDS	Chemical Dosing System
CVCS	Chemical and Volume Control System
CWS	Cooling Water System
HRS	Heat Rejection System
HX	Heat eXchanger
IBED	Integrated Blanket ELM/VS Coils and Divertor
IO	ITER Organization
LTM	Long-Term Maintenance
NBI	Neutral Beam Injector
NPSHa	Net Positive Suction Head Available
PHE	Plate Heat Exchanger
PHTS	Primary Heat Transport System
POS	Plasma Operating State
PRZ	Pressurizer
STM	Short-Term Maintenance
TBM	Test Blanket Module
TCS	Test and Conditioning State
TCWS	Tokamak Cooling Water System
TPS	Tritium Plant System
VV	Vacuum Vessel

1. Introduction

The primary goal of ITER is to demonstrate the scientific and technological feasibility of generating thermal power from deuterium and tritium plasmas. In doing so, the ITER machine represents a bridge between the future demonstration fusion nuclear power plants and the small-scaled experimental fusion facilities. Researchers will be able to test complex technologies including heating, control, diagnostics, cryogenics, and remote maintenance as well as to investigate plasmas in environments similar to those characterizing future fusion nuclear reactors. The machine is designed to produce about ten times ($Q = 10$) the thermal power supplied to the plasma. In this regard, the effective removal of thermal energy from all its components represents a key aspect of the performance of the machine.

Within this framework, ITER will be provided with a Cooling Water System (CWS) designed to remove a peak heat load of about 1200 MWt with an average of 540 MWt during a typical plasma pulse cycle [1,2]. The CWS consists of four systems: the Tokamak Cooling Water System

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Table 2.1
Mapping between CCWS-1 operating modes and ITER operational modes.

Mode	CCWS-1 Operating Mode			
	Cooling Mode		Off Mode	Maintenance Mode
	Full capacity	Partial capacity		
POS	X	X		
TCS		X		
STM		X		
LTM		X	X	X

(TCWS) [3], the Component Cooling Water System (CCWS), the Chilled Water System and the Heat Rejection System (HRS). Furthermore, the CCWS consists of the CCWS-1 and CCWS-2. CCWS-2, serving non-nuclear clients, is divided into four subsystems [4]: CCWS-2A, CCWS-2B, CCWS-2C and CCWS-2D [5–7]. CCWS-1 is a closed cooling loop responsible for transferring thermal loads from nuclear clients located in the Tokamak Complex, such as the TCWS, to the HRS, which discharges heat to the environment [8].

In this framework and following the work done in [9–11], a research campaign has been conducted to assess the thermal-hydraulic performance of CCWS-1 and contribute to its process design. The activity has been performed using the AFT Fathom 9 lumped-parameters code [12],

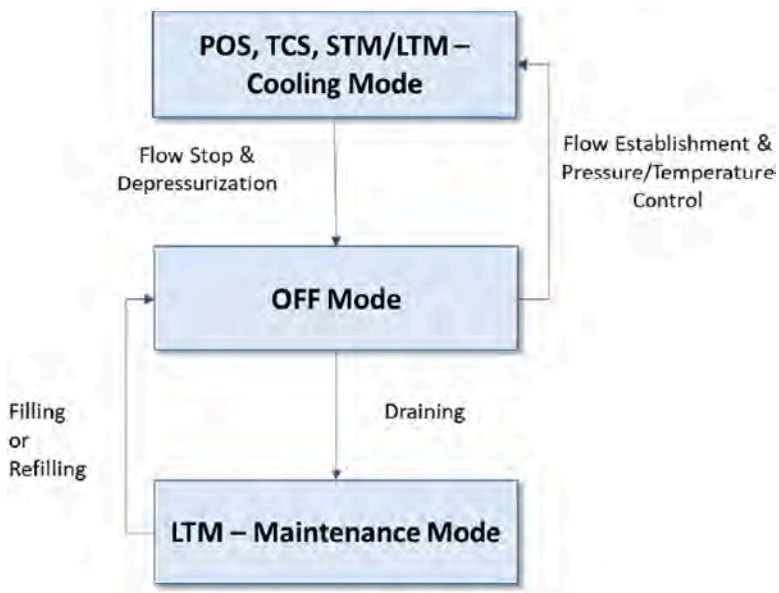

Fig. 2.1. Transition between CCWS-1 operating modes [1].

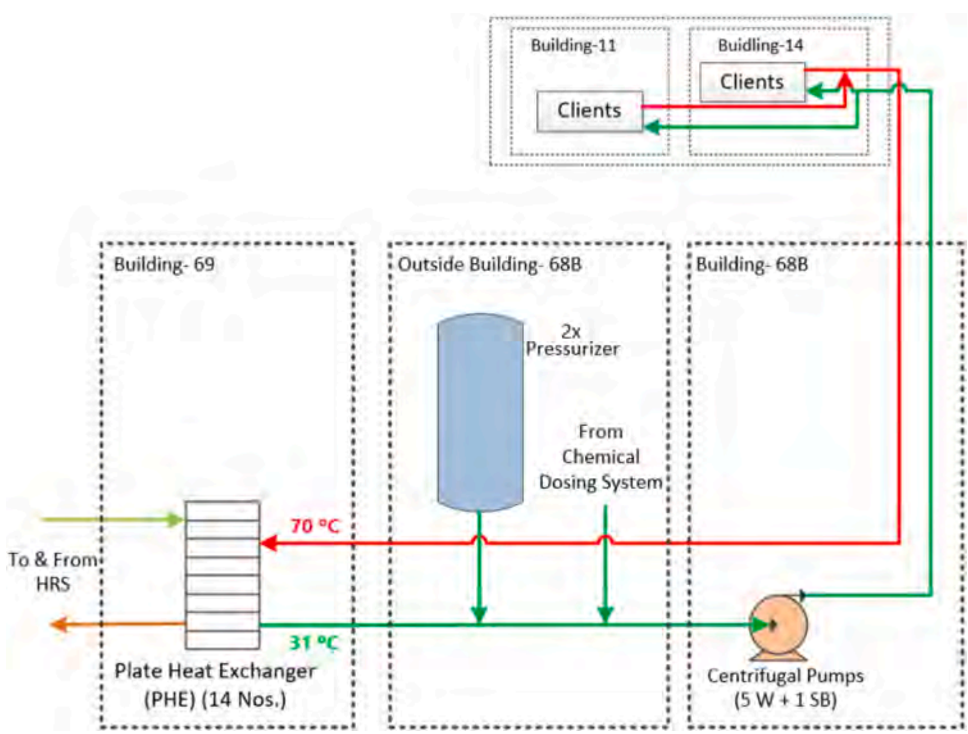

Fig. 2.2. CCWS-1 simplified layout [1].

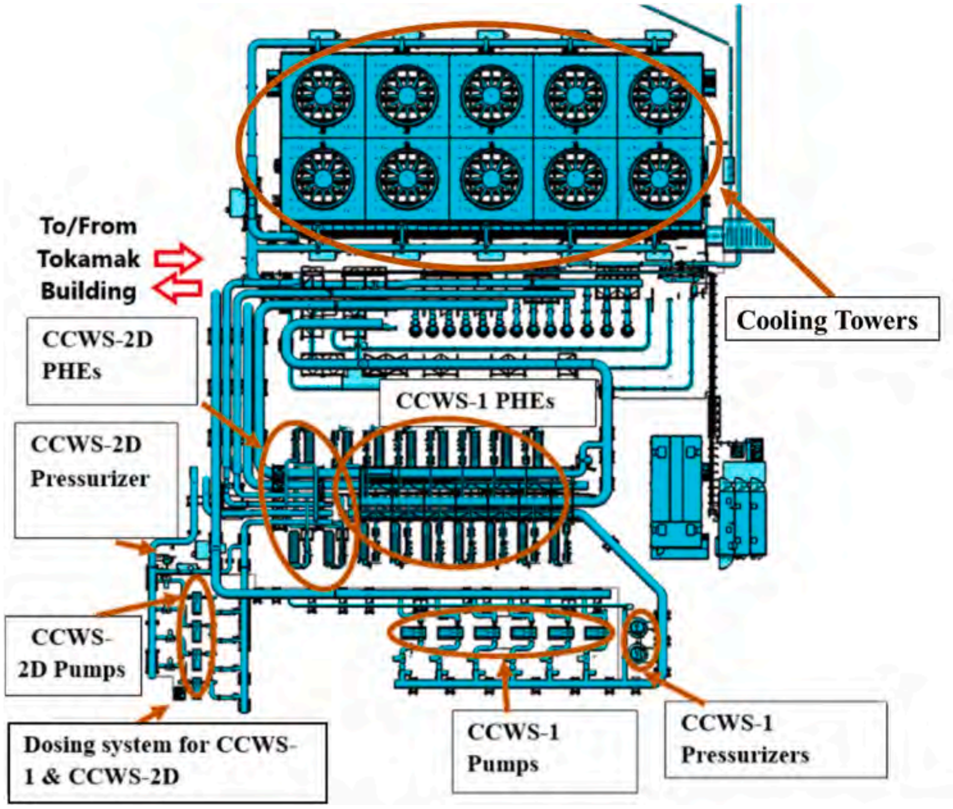

Fig. 2.3. CCWS-1 pipe routing outside Tokamak Building [1].

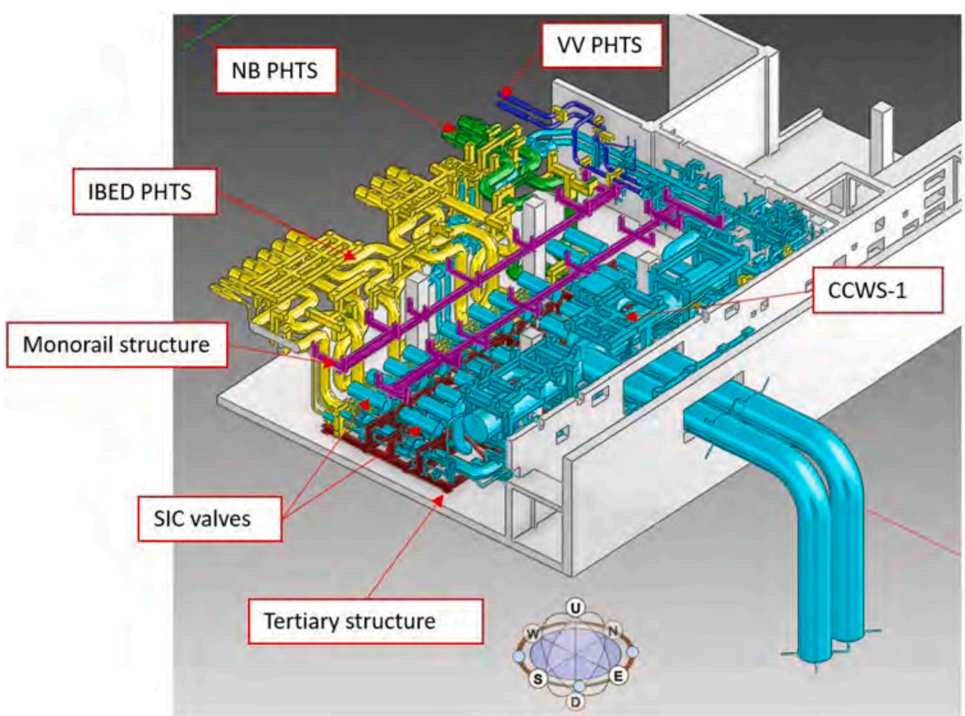

Fig. 2.4. Portion of CCWS-1 pipe routing inside Tokamak Building.

Table 2.2
Thermal-hydraulic requirements for CCWS-1 [1].

Thermal-hydraulic requirements	Unit	Value
Max total heat load	[MW]	988
Max coolant inlet temperature to clients	[°C]	31
Max coolant outlet temperature from clients	[°C]	80
Max coolant inlet pressure	[MPa(g)]	0.8
Max client pressure drop	[MPa]	0.4
Max total mass flow rate to clients	[kg/s]	6211

thermal-hydraulic simulation software to simulate steady-state and heat transfer of complex hydraulic systems.

In particular, the first phase of the activity has been mainly devoted to updating the geometry of the current Fathom model of CCWS-1 to make it consistent with the latest layout. Furthermore, the pressure drops, the required flow rates, the power of each client, the set points of each client control valve, flow coefficients (Cvs), and inherent characteristics of each valve have been updated in the Fathom model. Then, in a second phase the ITER operational modes have been simulated to verify the design and interface requirements in terms of coolant pressure and temperature to clients, velocity of the fluid inside pipes and to check the proper working of control valves.

The present work summarizes the thermal-hydraulic analyses campaign, describing the computational model, the hypotheses considered, the methodology adopted and the main outcomes as well as their critical discussion.

2. The CCWS-1 cooling loop

The CCWS-1 is a pressurized closed-loop cooling water system and part of the CCWS. It has the primary function of transferring thermal loads from its clients to the HRS maintaining coolant temperature, pressure, and flow rates within prescribed limits. In addition, it is designed to be capable of draining and refilling system components during maintenance and to provide sampling capability for tritium and activated corrosion products, which represent the sources of contamination from primary cooling systems.

During the fusion power operations, ITER is expected to operate following different operational modes: Plasma Operating State (POS), Test and Conditioning State (TCS), Short-Term Maintenance (STM) and Long-Term Maintenance (LTM) [11]. The ITER operational modes can be described in general as follows:

- **POS**: all the systems are in normal operation and at full load. It presents three variants: inductive, hybrid and non-inductive. The three variants are characterized by different heat loads transferred to the HRS. Among them, the inductive variant is the maximum plasma power scenario [13] and, therefore, inductive steady-state thermal-hydraulic conditions are considered to establish the maximum heat removal requirements.
- **TCS**: most of the systems are ready for test-pulsing with no plasma. Cooling systems are in low-flow, magnets can be operating and the access is very restricted and tightly controlled.
- **STM**: it is characterized by the stop of plasma operations for a short break (8h silent shift) or a few days of routine maintenance (<30 days). The magnets are not run through by electric current, but they remain cooled. Vacuum Vessel (VV) and cryostat are being actively pumped and the thermal shield is actively cooled.
- **LTM**: plasma operations are stopped for a long period (>30 days) for serious maintenance or upgrade after a significant nuclear decay period: all systems are locked safe, cryostat and VV are vented and magnets are off. Furthermore, decay heat is passively removed.

CCWS-1 is designed to operate in three operating modes: *cooling mode, off mode*, and *maintenance mode* [1]:

- *Cooling Mode*: the cooling system operates at full load or partial load following the requirements of the clients during the ITER operational modes: POS, TCS, STM and LTM.
- *Off Mode*: it is considered only during LTM, with no flow and no heat transfer. In that condition, CCWS-1 is filled with water and closed. During this mode, the system covers off-normal events where the flow rate of cooling water is stopped or unavailable (e.g. lack of flow rate). The system reaches the ambient temperature (minimum ambient temperature 5 °C) after a continued shutdown (LTM).
- *Maintenance Mode*: it is characterized by standard maintenance programs performed during LTM or in agreement with clients. The system will be depressurized at ambient conditions once it has been completely or partially drained and secured as needed for maintenance. To prevent corrosion, the opened portion for maintenance is filled with air and the closed portion is filled with nitrogen.

Table 2.3
List of clients served by CCWS-1 and heat load distribution.

Number [-]	Name	Heat load [MW]				
		POS		**TCS**	**STM**	**LTM**
		Nominal	**Design**			
1	*TCWS Auxiliary Cooling Header*	2.8	2.8	2.8	1.75	1.75
2	*IBED PHTS B1 HX*	217.1	245	10	0	0
3	*IBED PHTS B2 HX*	217.1	245	10	0	0
4	*IBED PHTS B3 HX*	217.1	245	10	0	0
5	*IBED PHTS B4 HX*	217.1	245	10	0	0
6	*CCWS-1A HX*	5.74	5.74	5.74	5.74	5.74
7	*CVCS IBED HX & Sample Coolers*	2	2	2	2	2
8	*NBI PHTS HX*	89.4	89.4	74.4	4	4
9	*VV PHTS HX & Volume Control System HX*	13.6	13.6	5	8.7	8.7
10	*TBM Primary Cooling System Outside Port Cell*	4.82	4.82	4.82	0.8	0
11	*TPS Components – Helium Compressor*	0.5	0.5	0.5	0.5	0.5
12	*Drying System*	0	0	0	0	3.46
13	*Drying Compressor*	0	0	0	0	0.27
14	*IBED PHTS B5 Baking HX*	0	0	0	5.8	5.8
15	*TPS Components - Electrolysers*	0.66	0.66	0.66	0.66	0.66
16	*Roughing pump of Vacuum System*	0.04	0.04	0.025	0.15	0.15
17	*Vacuum System A*	0.015	0.015	0.015	0.015	0.015
18	*Vacuum System B*	0.015	0.015	0.015	0.015	0.015
19	*Vacuum System C*	0.015	0.015	0.015	0.015	0.015

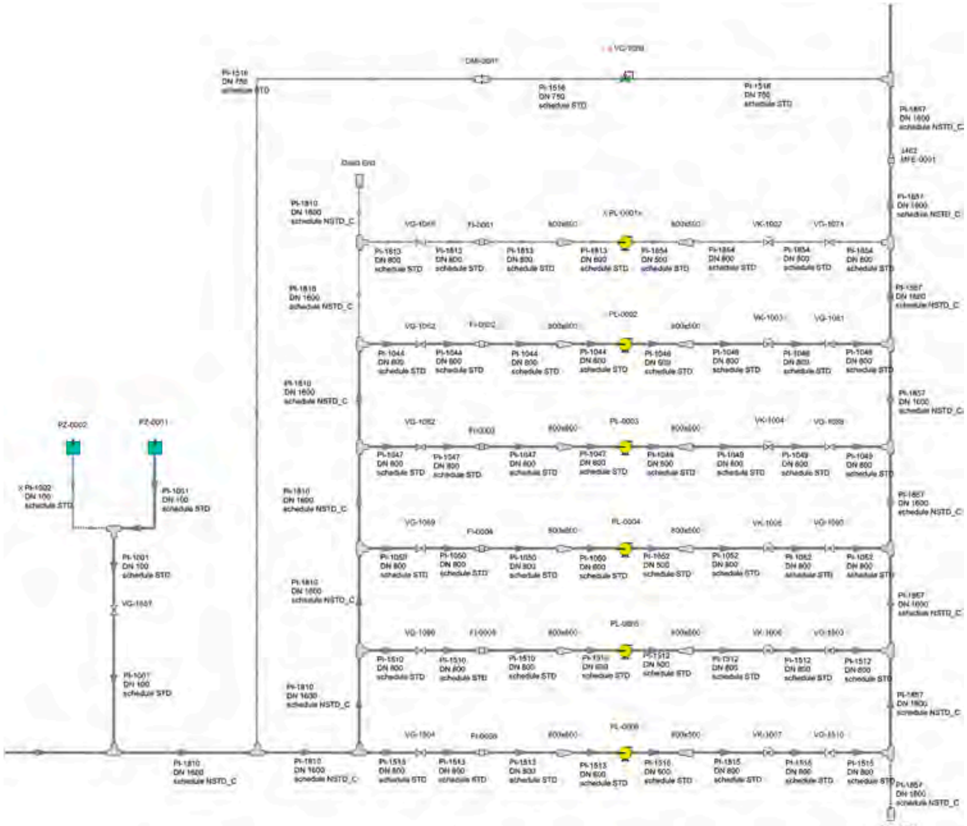

Fig. 3.1. Detail of the Fathom model of pumps and PRZs.

Table 2.1 provides the mapping between the CCWS-1 operating modes and ITER operational modes. Fig. 2.1 reports the CCWS-1 operating mode flow chart with the transition between cooling mode, off mode and maintenance mode described above.

The CCWS-1 is equipped with 6 horizontal centrifugal pumps, 14 Plate Heat Exchangers (PHEs), 2 Pressurizers (PRZs), and a Chemical Dosing System (CDS). The cooling system interfaces with clients through 19 connections. Each client is characterized by one Heat eXchanger (HX) [3]. A general scheme of the cooling loop is presented in Fig. 2.2.

The six pumps present a rated nominal capacity of 1247 kg/s (4510 m^3/h) and a rated nominal pressure head of 83 m each. They provide cooling water to clients at the required flow rate. Since clients will require a different total flow rate depending on the machine's operating mode, a recirculation bypass line has been provided to maintain the flow rate in the allowable pump's operating region. In this line, an orifice has been installed downstream of the control valve to create a constant pressure drop to match that of the system and to protect the pumps when the lowest flow rate is required by the clients.

The PHEs transfer thermal power to the HRS and control the supply coolant temperature of CCWS-1. They are sized for the total heat load during POS conditions. The heat transfer is controlled by varying the speed of HRS system pumps. On the other hand, PHEs can increase the heat transfer surface area adding extra plates in case of future needs.

Two PRZs control the pressure of the system and permit the expansion of water volume during different scenarios. They also maintain the suction pressure at the inlet of the pump and set a pre-charge pressure to avoid cavitation at the pump impeller. Each PRZ has a volume of 25 m^3 and it is based on the water volume expansion of the system during full load conditions.

The CDS is designed to maintain the pH of the coolant between 8.5 and 9 to avoid corrosion by adding Sodium Hydroxide (NaOH).

Carbon steel piping has been considered for the portion of CCWS-1 that lies outside the Tokamak Complex, presented in Fig. 2.3. While, for the portion of the cooling loop inside the Tokamak Complex, stainless steel piping has been considered to reduce potential interference with electromagnetic fields. In Fig. 2.4. a portion of the CCWS-1 pipe routing inside the Tokamak Complex is presented.

The system is equipped with control valves, isolation valves, check valves, and pressure relief valves. Double isolation valves are provided for all primary clients to isolate the CCWS-1 system during a possible event of Heat eXchanger tube break and to meet Safety Importance Class requirements. Two isolation valves (actuated or check valves) are installed in pipes penetrating nuclear confinement barriers inside the Tokamak Complex to close and protect the penetration during safety-relevant events (Nuclear Boundary Confinement Protection Valves). Manually operated gate valves are provided in the suction line of the individual pumps; instead, motor-operated gate valves are provided in the pump discharge lines. Motor-operated gate valves are provided at the makeup flow of the PRZs and motor globe valves are provided for sampling and draining purposes.

The cooling system is designed to feed its served clients with cooling water at 31 °C with a maximum inlet pressure of 0.8 MPa(g), except for vacuum systems clients with a maximum inlet pressure of 1.0 MPa(g), to remove a total thermal power of 988 MW during POS. The maximum client pressure drop is 0.4 MPa, except for the vacuum systems clients where the maximum pressure drop is equal to 0.5 MPa. Table 2.2 presents the CCWS-1 thermal-hydraulic requirements and Table 2.3 shows the list of clients served by CCWS-1 with the corresponding heat load for each ITER operational mode.

During POS, the total heat load to CCWS-1 from the Integrated Blanket ELM/VS Coils and Divertor (IBED) Primary Heat Transport System (PHTS) HXs and VV PHTS HX & Volume Control System HX is limited to 881.8 MW. The heat load from the IBED PHTS HXs branches is not uniformly distributed and it is characterized by a peak heat load of 245 MW from a single IBED PHTS HX branch. In this case, the outlet coolant temperature could reach 80 °C. In this view, for the design of the

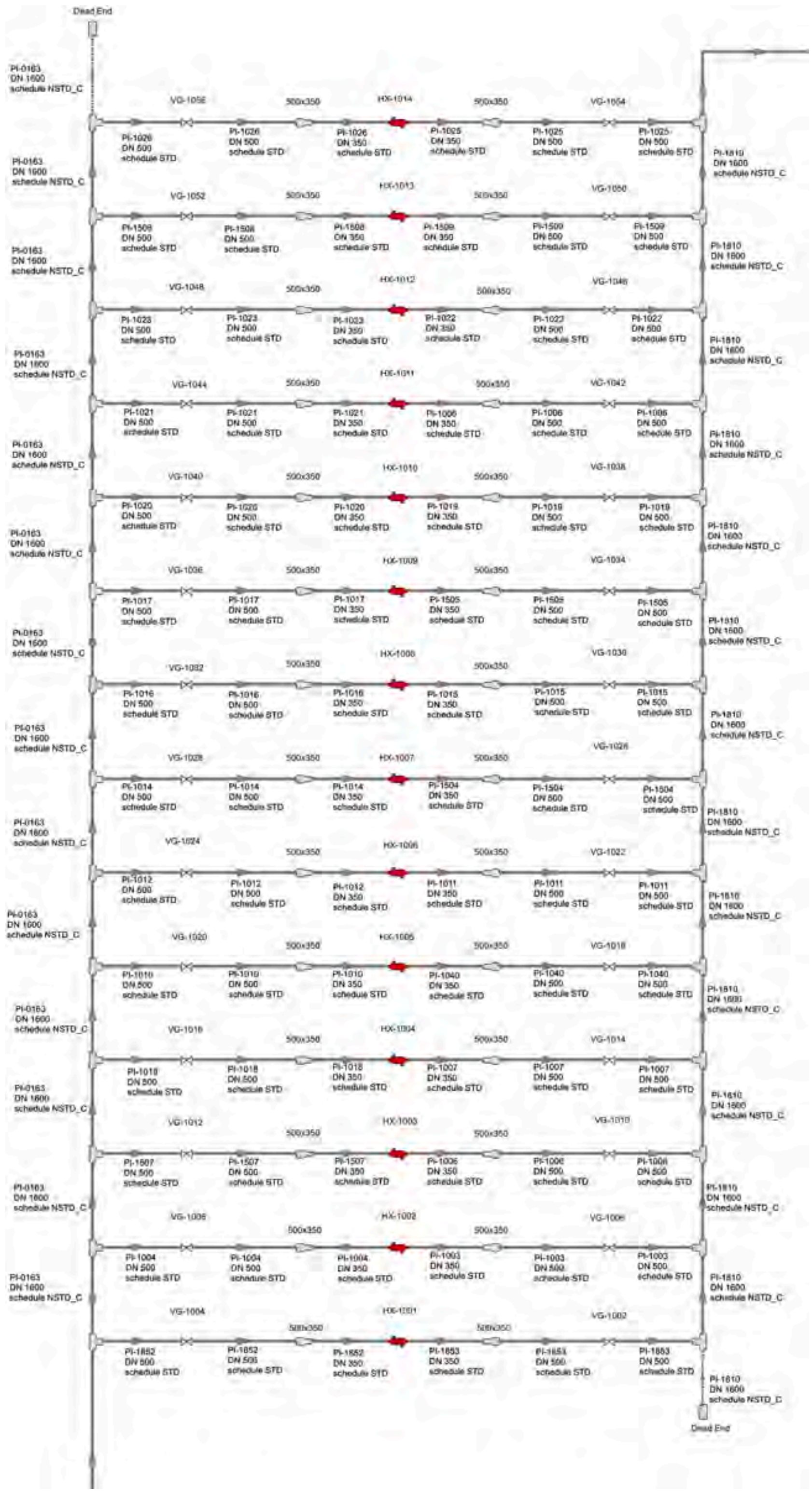

Fig. 3.2. Detail of the Fathom model of PHEs.

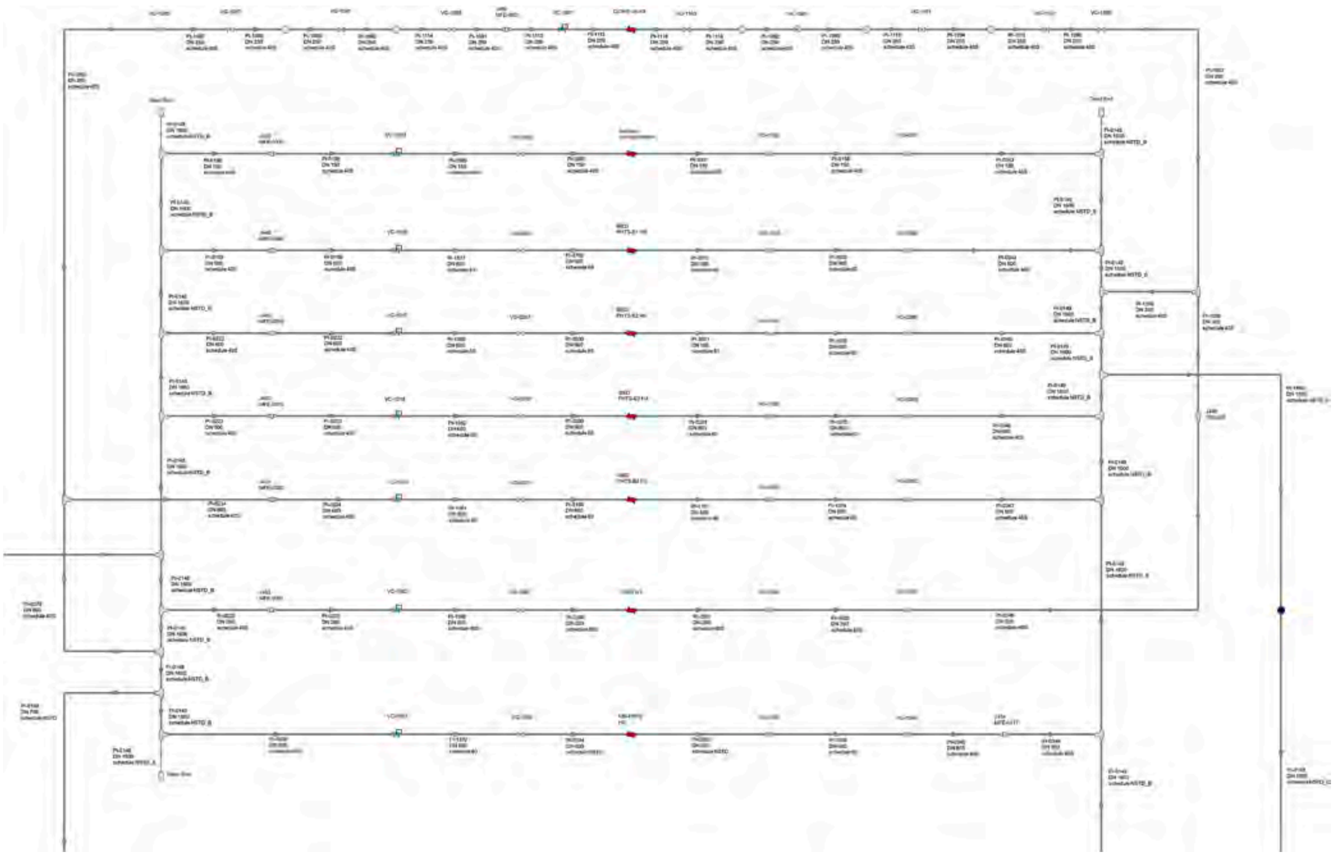

Fig. 3.3. Detail of the Fathom model of CCWS-1 inside the Tokamak Building (a).

cooling system and the thermal-hydraulic analysis presented in this paper, a heat load of 245 MW has been assumed in the Fathom model for each of the four IBED PHTS HXs branches, as presented in Table 2.3.

3. Fathom model of the CCWS-1

The research activity has been carried out adopting the thermal-hydraulic model of CCWS-1 developed by ITER Organization (IO) to simulate its behaviour under ITER operational modes using the AFT Fathom 9 lumped-parameters code. It is a thermal-hydraulic simulation software used to simulate steady-state hydraulics and heat transfer of complex systems. It uses the Newton-Raphson method to obtain the solutions of the pipe network system. The method employs the conservation of mass equation and the momentum balance equation. After a solution is obtained, a final check is made by the software whereby the mass flow into each node is checked for balance. If heat transfer is modelled, the software performs a final energy check for each junction.

The Fathom code is widely used in common engineering practice for the study of complex thermal-hydraulic networks of nuclear and non-nuclear installations. Concerning its application in the nuclear industry, the code is provided by a Nuclear Verification and Validation package to ensure its accuracy for safety-related applications [14]. The Verification is performed by the official supplier. On the other hand, the Validation is done by the code user, comparing the code output against selected test cases [15].

As already mentioned, the activity has been initially focused on updating the current Fathom model. The updates have aimed at aligning the Fathom model with the latest design developments of the CCWS-1 system and reported in the latest available P&ID [16] and 3D model and mainly concerned the geometric characteristics of the pipes, i.e. lengths and diameters as well as their layout. Furthermore, the attention has been focused on updating the Cvs of isolation and control valves of the portion of the system within the Tritium Building that is part of the Tokamak Complex.

Concerning purchased and installed components, such as the pumps [17], PRZs [18,19] and PHEs [20], placed outside the Tokamak Building, they have been modelled in Fathom considering the available datasheets, isometrics, and sizing calculations. In this regard, the six horizontal main pumps have been modelled using the pump component available in Fathom, PRZs as “reservoir” components imposing the system pressure and the PHEs have been modelled as HX junctions, imposing a controlled downstream temperature of 31 °C. In Fig. 3.1a detail of the Fathom model of the pumps and PRZs. Fig. 3.2 shows the detail of the Fathom model of PHEs’ layout.

Pressure loss information for pipes and their fittings is calculated by the Fathom code based on the libraries implemented within the code itself and the geometric and hydraulic characteristics that are provided as input to the code during the numerical model development phase. The former refers to the main reference handbooks for the study of complex hydraulic networks, such as [21,22]. Properties of pipes, including nominal diameter, schedule, length, and information on fittings such as tees, reducers, expanders, strainers, orifices, and flow meters have been extracted from the latest available P&ID [16].

Isolation and check valves have been modelled as valves with a “user specified” constant Cv. The Cvs at full opening have been extracted from available data [23–26].

Control valves have been modelled using the “flow control” valve type available in Fathom which permits the implementation of a tabular valve curve, where the Cv is given as a function of the opening percentage of the valve. These components adjust their Cv based on the target mass flow rate between zero and a user-specified maximum value associated with the fully open valve. Since the datasheets of these valves are not available yet, their Cvs at full opening have been extracted from available data. Preliminary inherent characteristic curves, presented in

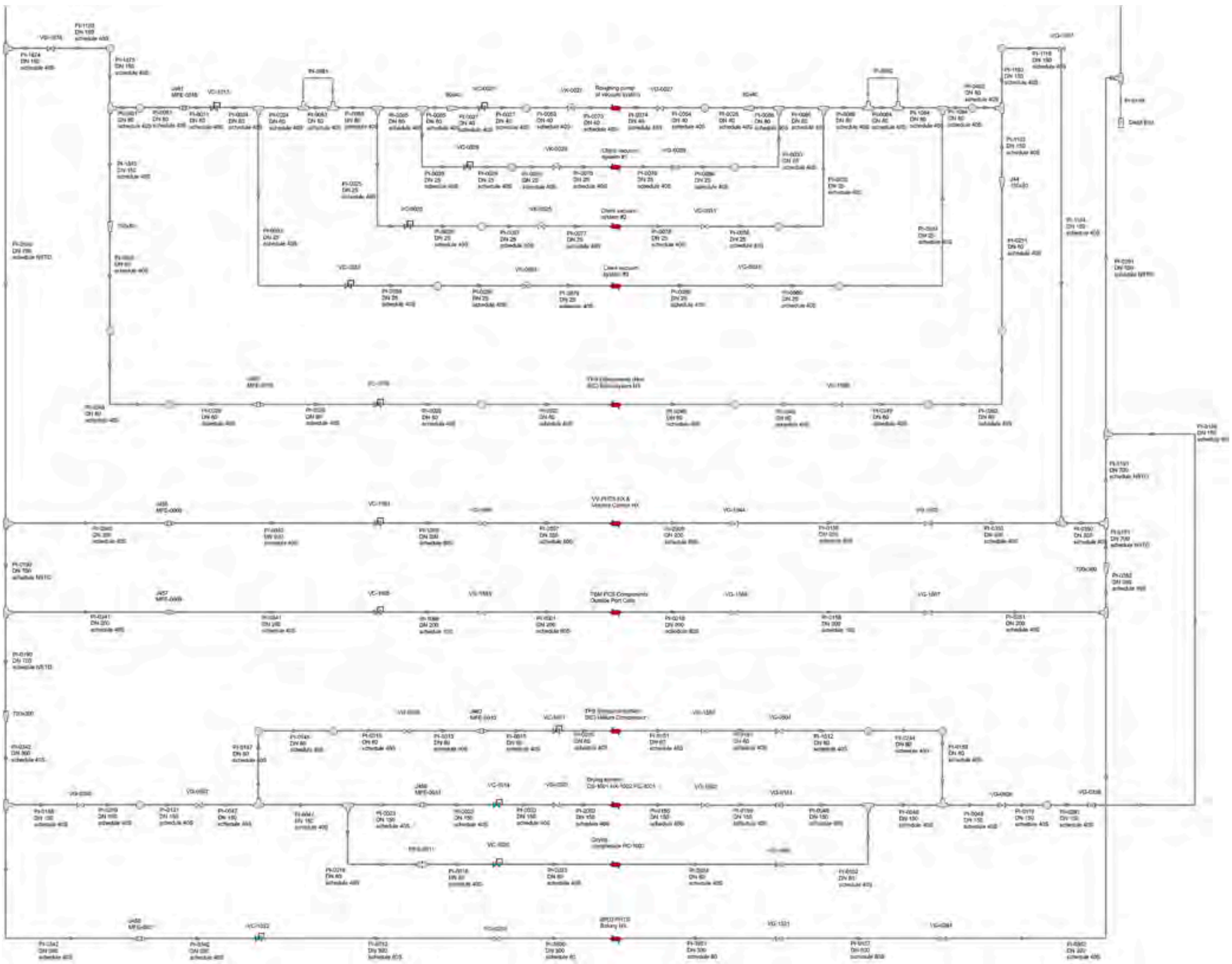

Fig. 3.4. Detail of the Fathom model of CCWS-1 inside the Tokamak Building (b).

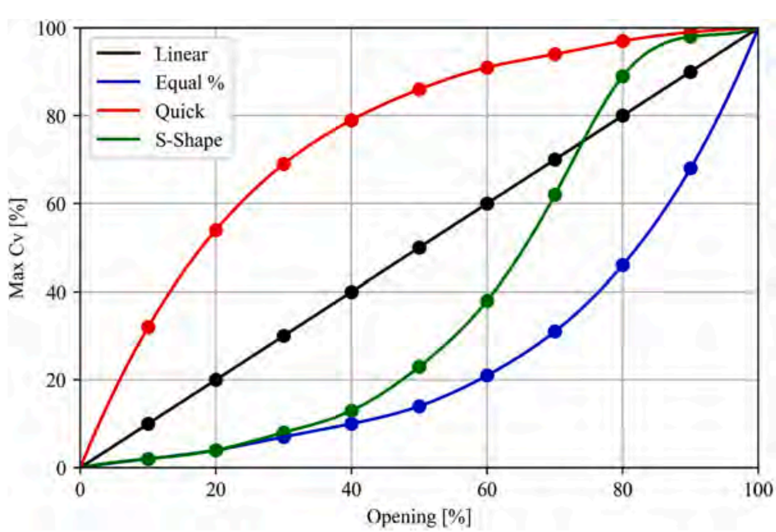

Fig. 3.5. Generic control valve inherent characteristics.

Fig. 3.5, have been considered for the control valves.

Fig. 3.3 and Fig. 3.4 present a detail of the Fathom model for the portion of CCWS-1 inside the Tokamak Building. Fathom HX junctions have been considered to model system clients as well as to model PHEs. In HX junctions, it is necessary to specify the thermal loads to be removed as well as the quadratic curve resistance of the component. This

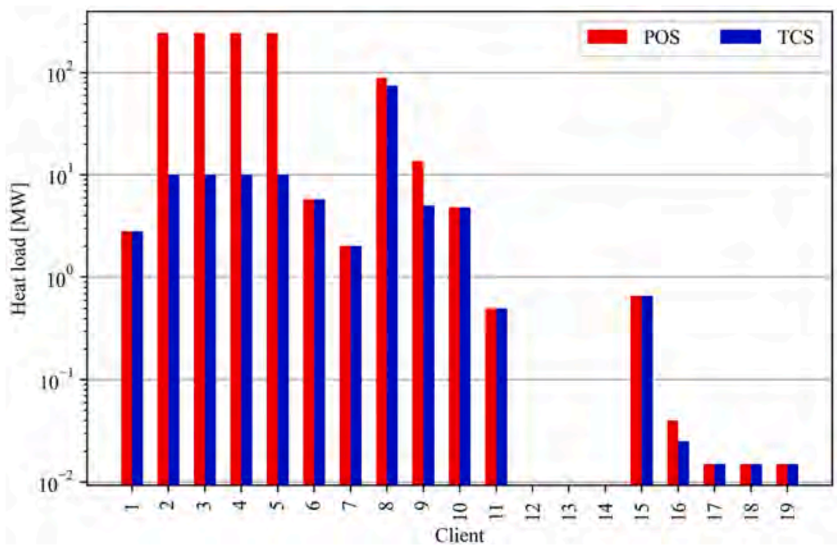

Fig. 4.1. Heat load from clients during POS and TCS.

Table 4.1
Summary of pumps' parameters during POS and TCS.

Name	Status	Q [m^3/h]	H [m]	NPSHa [m]	η [%]
PL-0001	Stand-by	–	–	–	–
PL-0002	In operation	4515	80.39	40.02	81.37
PL-0003	In operation	4503	80.56	40.01	81.39
PL-0004	In operation	4490	80.73	40.00	81.41
PL-0005	In operation	4474	80.94	39.92	81.43
PL-0006	In operation	4482	80.84	39.71	81.42

latter is calculated by Fathom from the total pressure drop allowed by the client at the nominal flow rate. The nominal flow rate, the allowable pressure drop of the client and the thermal loads of each client are reported in the interface sheets [27–32] and CCWS-1A System Sizing Calculation Report [33]. The working fluid model used is the "ASME '97 Water Tables". This fluid model has been developed based on the data from ASME International Steam Tables for Industrial Use based on [34].

4. Thermal-hydraulic analyses campaign on CCWS-1

To assess the thermal-hydraulic response of the system under steady-state conditions, POS, TCS, STM and LTM scenarios have been simulated.

To ensure proper system operation, the functioning operation point of pumps as well as the proper functioning of PHEs have been evaluated.

The clients' interface requirements have been verified in terms of coolant flow rate, coolant inlet operating pressure and coolant inlet and outlet operating temperatures for each client.

Furthermore, the correct operation of the control valves is assessed by comparing the opening percentage calculated by Fathom with the desired operating range. In this regard, it is worth highlighting that it is common practice in control valve sizing to make sure that the valve never has to operate close to a fully closed or fully open position (i.e., 0 or 100 percent opening degree) during normal operation. The purpose is to utilize as much of the valve's control range as possible while maintaining a reasonable but not excessive safety factor [35]. Therefore, valve sizes should ideally be selected such that under nominal operating conditions, they operate with an opening degree of around 60 %–70 % and that under none of the conditions expected during normal

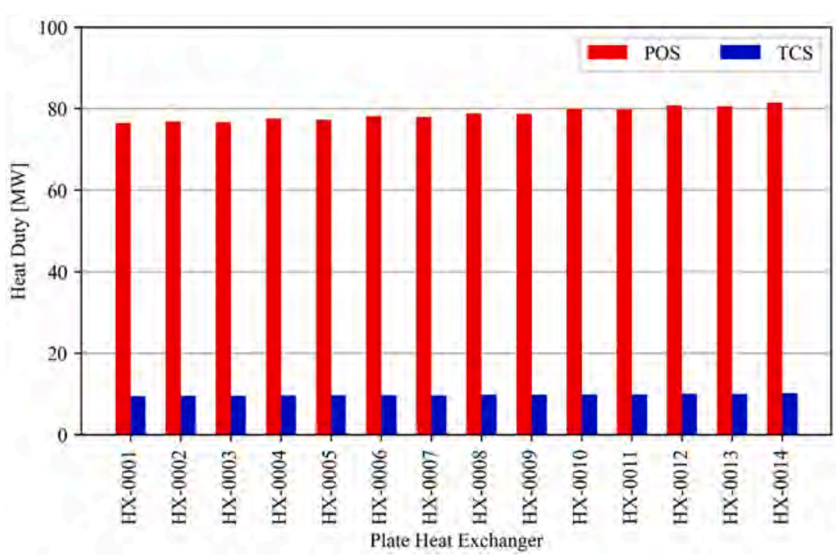

Fig. 4.2. Comparison of PHEs heat load distribution between POS and TCS.

Table 4.2
Main parameters of heat load distribution in PHEs during POS and TCS.

Parameter	Unit	POS	TCS
Total heat load	[MW]	1101.2	137.0
Maximum heat load	[MW]	81.5	10.2
Minimum heat load	[MW]	76.5	9.5
Relative maximum variation	[%]	6.62	6.75
Average heat load	[MW]	78.7	9.8
Standard deviation	[MW]	1.6	0.2
Coefficient of variation	[-]	0.02	0.02

operation, the valve operates with an opening degree below or above certain limits that are chosen by the designer. Typically, one seeks to operate between a minimum limit that usually ranges between 10 and 20 percent and a maximum limit that ranges between 80 and 90 percent.

The CCWS-1 design team established by design choice that control valves should operate in the 20–80 % range in accordance with common engineering practice followed in sizing these components.

The piping of the circuit is designed to allow fluid velocities between 0.5 and 5 m/s. One of the scopes of the present analyses is to assess that the velocity inside pipes respects these thresholds. High velocity in pipelines can lead to a plethora of operational and maintenance problems such as noise, vibration, erosion of pipe material, and combined erosion-corrosion problems. On the other side, with very low flowing velocities, phase separation will occur of the solid particles that could come from corrosion with the higher density solid particles tending to settle down at the bottom of a horizontal pipe run.

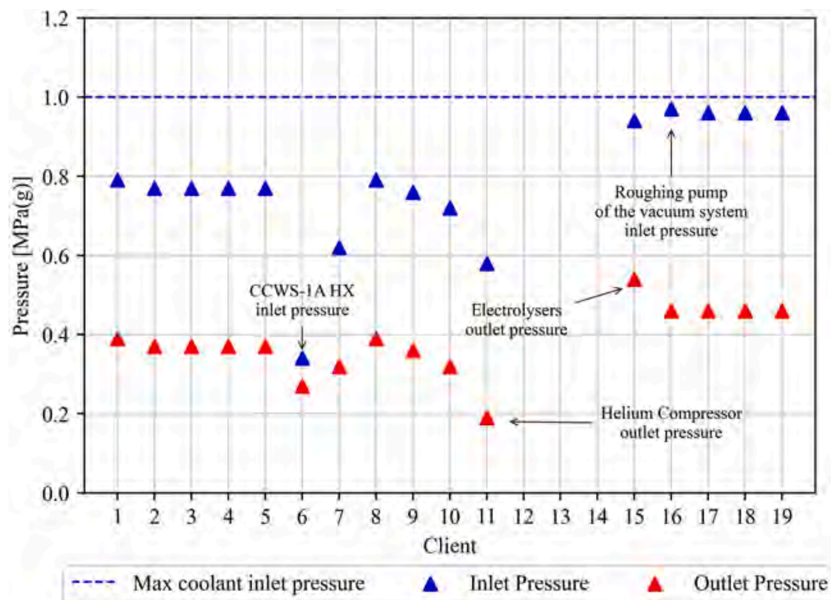

Fig. 4.3. Coolant operating pressure for clients during POS.

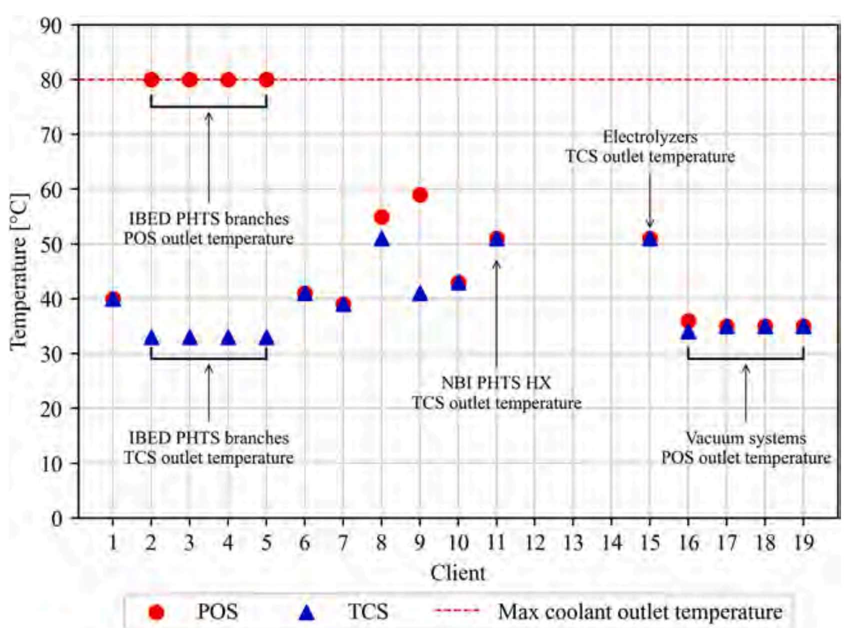

Fig. 4.4. Coolant operating outlet temperature for clients during POS and TCS.

Table 4.3
List of control valves of CCWS-1.

Control Valve	Scope
VC-1009	Control flow rate to pump bypass line
VC-1023	Control flow rate to TCWS Auxiliary Cooling Header
VC-1006	Control flow rate to IBED PHTS B1 HX
VC-1017	Control flow rate to IBED PHTS B2 HX
VC-1018	Control flow rate to IBED PHTS B3 HX
VC-1019	Control flow rate to IBED PHTS B4 HX
VC-1091	Control flow rate to CCWS-1A HX
VC-1002	Control flow rate to CVCS IBED HX & Sample Coolers
VC-1003	Control flow rate to NBI PHTS HX
VC-1015	Control flow rate to Pump of Vacuum System and Vacuum Systems
VC-1016	Control flow rate to TPS Components - Electrolysers
VC-1004	Control flow rate to VV PHTS HX & Volume control
VC-1005	Control flow rate to TBM Primary Cooling System Outside Port Cell
VC-1011	Control flow rate to TPS Components - Helium Compressor
VC-1014	Control flow rate to Drying System
VC-1020	Control flow rate to Drying Compressor
VC-1022	Control flow rate to IBED PHTS B5 Baking HX

4.1. Scenario 1 and Scenario 2: POS and TCS

As previously introduced in Section 2, during POS the machine works at full load conditions while, during TCS, it works at partial load conditions. It should be noted that the POS load conditions refer to the pulse phase; during the dwell phase the total heat loads from the clients is about 40 MW and the flow rates to clients remain the same as in the pulse phase. Fig. 4.1 shows the heat load distribution from clients to CCWS-1 during POS and TCS. During POS, the maximum heat load is associated with IBED PHTS with 245 MW for each branch (note that each client 2–3–4–5 is constituted by two HXs, see ref. [3]). On the other hand, the maximum heat load during TCS is associated with Neutral Beam Injector (NBI) PHTS HX with 74.4 MW. According to Table 2.3, the Drying System, Drying Compressor and IBED PHTS Baking HX are not served by CCWS-1 during POS and TCS.

During POS and TCS, five pumps are operating, and one remains on standby. A total of 6211.4 kg/s are required by the clients and then, the recirculation bypass line should divert an excess mass flow rate of 23.6 kg/s to maintain the pumps at their nominal regime. Nevertheless, the recirculation bypass line has been considered closed, imposing no flow rate bypassed due to the extremely low velocities that would be generated in the recirculation line, characterized by a DN750. This choice does not have implications for the proper functioning of pumps in terms of efficiency, which is about 81 % for each operating pump as shown in Table 4.1. This latter presents the key quantities characterizing pump operation in POS and TCS, such as the pump head (denoted as "H"), the Net Positive Suction Head Available (NPSHa) and the overall efficiency (denoted as "η"). It should be noted that POS and TCS are characterized by the same mass flow rate to clients and, for this reason, pump operating points are the same between POS and TCS.

The PHEs have been modelled to ensure a fixed outlet temperature of 31 °C. Then, the Fathom code enables the mass flow through each PHE and thus its heat duty to be calculated. Fig. 4.2 presents the head load distribution through PHEs during POS and TCS while Table 4.2 reports the main parameters of the heat load distribution of PHEs. It is underlined that the total heat load discharged to the HRS is 1102.2 MW during POS (obtained considering 245 MW for each IBED PHTS branch, as specified in Section 2) and 137.0 MW during TCS with an average heat load of 78.7 MW and 9.8 MW, respectively. The distribution is characterized by a relative maximum variation of 6.62 % during POS and 6.75 % during TCS. In this regard, the heat load goes up between the first and the last PHE due to the flow distribution through the PHEs which depends on the PHEs' layout, presented in Fig. 3.2. It consists of an inlet header, 16 parallel branches connected to each PHE and an outlet header. Therefore, as the PHEs are arranged in parallel, the mass flow rate through each branch and, consequently, the heat load on each PHE is tightly connected to the pressure drops within the other branches in parallel.

In Fig. 4.3 the coolant inlet and outlet operating pressure for each client during POS is presented. Among the clients, the coolant to roughing pump of the vacuum system is characterized by maximum coolant inlet operating pressure, with a value of 0.96 MPa(g) while CCWS-1A HX is characterized by the minimum coolant inlet operating pressure, with a value of 0.34 MPa(g). The minimum outlet operating pressure is associated with the coolant from the Helium Compressor of the Tritium Plant System (TPS), with a value of 0.19 MPa(g), while the maximum is 0.54 MPa(g) associated with the TPS' Electrolysers. The distribution of the inlet and outlet operating pressure appears to be variable as it depends mainly on the layout of the system and the arrangement of clients on each level of the Tokamak Building.

The coolant inlet and outlet operating pressure distribution during TCS is very similar to those presented during POS and, for this reason, it is not presented.

Fig. 4.4 shows the coolant outlet operating temperature for each client during POS and TCS. In this regard, it should be noted that the coolant inlet operating temperature for each client is 31 °C both during POS and TCS. During POS, the maximum outlet operating temperature is

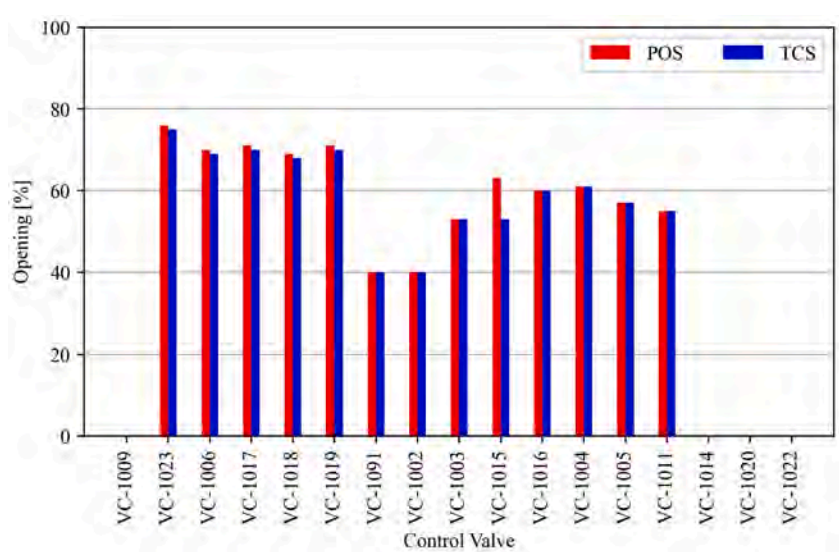

Fig. 4.5. Control valve opening percentage during POS and TCS.

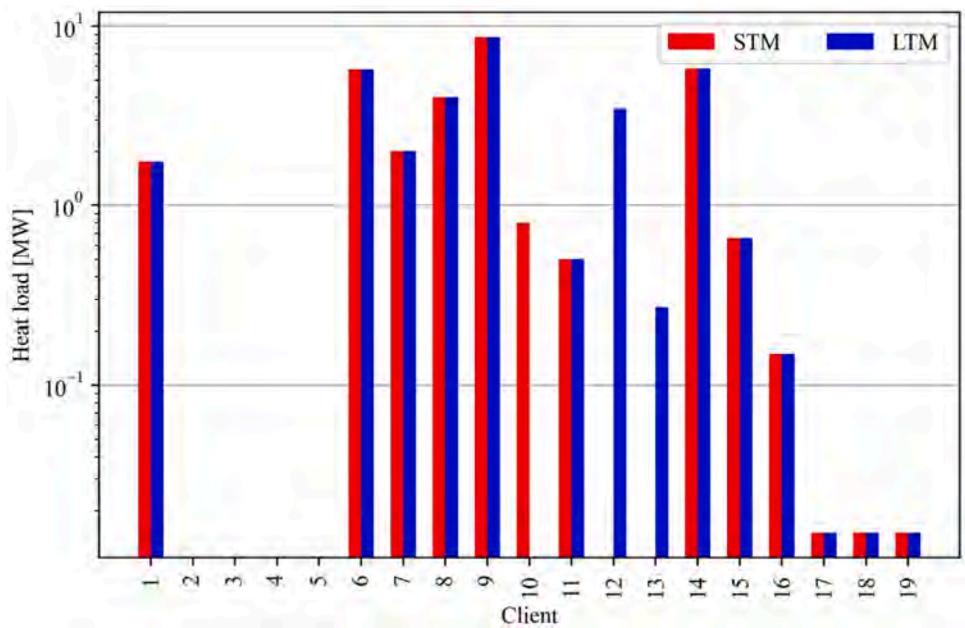

Fig. 4.6. Heat load from clients during STM and LTM.

Table 4.4
Summary of main pumps' parameters during STM.

Name	Status	Q [m^3/h]	H [m]	NPSHa [m]	η [%]
PL-0001	Stand-by	–	–	–	–
PL-0002	In operation	3478	92.68	41.10	77.85
PL-0003	In operation	3494	92.52	41.08	77.97
PL-0004	Stand-by	–	–	–	–
PL-0005	Stand-by	–	–	–	–
PL-0006	Stand-by	–	–	–	–

Table 4.5
Summary of main pumps' parameters during LTM.

Name	Status	Q [m^3/h]	H [m]	NPSHa [m]	η [%]
PL-0001	Stand-by	–	–	–	–
PL-0002	In operation	3556	91.89	41.04	78.03
PL-0003	In operation	3572	91.72	41.01	78.14
PL-0004	Stand-by	–	–	–	–
PL-0005	Stand-by	–	–	–	–
PL-0006	Stand-by	–	–	–	–

80 °C and it is associated with outlet coolant from IBED PHTS branches, while the minimum is 35 °C and is associated with the coolant flowing from vacuum systems. During TCS, the maximum outlet coolant operating temperature is 51 °C and it is associated with NBI PHTS HX and Electrolysers, while the minimum outlet operating temperature is 33 °C and is associated with IBED PHTS branches.

In general, during POS and TCS, the system requirements in terms of maximum coolant inlet operating temperature and pressure, maximum outlet operating temperature and maximum client pressure drop, defined in Table 2.2, have been respected.

In Table 4.3, the list of control valves in the cooling system and the scope of each valve are reported. Then, in Fig. 4.5 the percentage of each of them calculated by Fathom during POS and TCS is presented.

All control valves present an opening percentage within the selected operating range of 20–80 %. Valve VC-1009, which regulates the flow rate of the pump bypass recirculation line, has been considered closed due to the low velocity of the fluid, as specified above. Moreover, control valves VC-1014, VC-1020 and VC-1022, regulating flow rate to the Drying System, Drying Compressor and IBED PHTS Baking HX, are closed. Control valve VC-1023, regulating flow rate to TCWS Auxiliary Cooling Header, presents the maximum opening percentage, equal to 76 %. On the other hand, VC-1091 and VC-1002, controlling the flow rate to CCWS-1A HX and Chemical and Volume Control System (CVCS) IBED HX & Sample Coolers present the minimum opening percentage, equal to 40 %.

Finally, the analysis of the fluid velocity has been conducted only during POS since it is the most demanding scenario for which the system was designed. This analysis highlighted that some portions present a fluid velocity higher than 5 m/s and others <0.5 m/s. For the portion of CCWS-1 placed outside the Tokamak Complex, fluid velocity exceeds the target of 4.5 m/s in the connections between PHEs and their reducer/expander. In this portion, velocities can reach about 5 m/s. Other portions where the velocity exceeds the target value are the outlet connections between pumps and expanders, where velocities can reach 5.3 m/s. The velocity is less than the minimum target velocity of 0.5 m/s in the PHEs inlet man header and for the specular PHEs outlet main header, with a velocity of 0.24 m/s and 0.22 m/s respectively. On the other hand, for the portion of CCWS-1 placed inside the Tokamak Complex, the fluid velocity exceeded the target velocity in the lines going to IBED PHTS clients, with a value of 5 m/s and for the first portion of the subheader connected to the inlet main header, serving CCWS-1A and IBED PHTS line 4 clients. Then, low velocity has been identified in the first and last portion of the client inlet and outlet main header with a velocity of 0.04 m/s and 0.46 m/s respectively, in a portion of the line that goes to Level 4 of the Tokamak Complex with values of velocity of 0.32 and 0.33 m/s. In addition, low fluid velocities were found in portions of the system placed before the reducer and after the expanders, with fluid velocity values. However, both high and low fluid velocity values have been observed for short stretches of piping considering that they are not critical for the correct functioning of the cooling system.

4.2. *Scenario 3 and Scenario 4: STM and LTM*

As described in Section 2, STM and LTM are characterized by the stop of plasma operations for short and long periods, respectively. In this regard, IBED PHTS HXs clients are not served by CCWS-1 during these scenarios. Furthermore, the Test Blanket Module (TBM) Primary Cooling System Outside the Port Cell is served by CCWS-1 only during STM

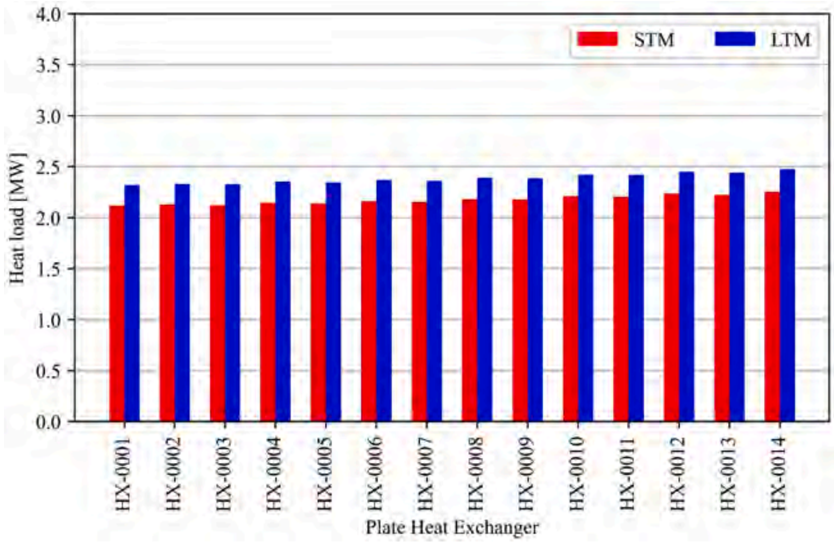

Fig. 4.7. Comparison of PHEs heat load distribution between STM and LTM.

Table 4.6
Main parameters of heat load distribution in PHEs during STM and LTM.

Parameter	Unit	STM	LTM
Total heat load	[MW]	30.5	33.4
Maximum heat load	[MW]	2.3	2.5
Minimum heat load	[MW]	2.1	2.3
Relative maximum variation	[%]	6.53	6.64
Average heat load	[MW]	2.2	2.4
Standard deviation	[MW]	0.045	0.05
Coefficient of variation	[-]	0.02	0.02

and the Drying System and the Drying Compressor are served by CCWS-1 only during LTM.

In Fig. 4.6 the distributions of the head loads from the clients during STM and LTM are reported. STM and LTM are characterized by a maximum heat load of 8.70 MW associated with VV PHTS HX & Volume control client.

A total of 1547.7 kg/s and 1640.2 kg/s are required by clients during STM and LTM. Then, two pumps are considered active and four in stand-by. Moreover, the activation of the pump bypass recirculation line has been considered to raise pump efficiency. Then, a mass flow rate of 380 kg/s is bypassed by the recirculation line. Table 4.4 and Table 4.5 respectively show the key quantities characterizing pump operation in STM and LTM.

Fig. 4.7 shows the heat load distribution through PHEs. As reported in Table 4.6, the total heat load to HRS is 30.5 MW and 33.4 MW respectively during STM and LTM. The average heat load associated with a PHE is 2.2 MW during STM and 2.4 MW during LTM. The distribution is characterized by a relative maximum variation of 6.53 % and 6.64 respectively during STM and LTM.

In Fig. 4.8 the coolant inlet and outlet operating pressure for each client during STM is presented.

The roughing pump of the vacuum system is characterized by the maximum coolant inlet operating pressure of 0.83 MPa(g). The minimum coolant inlet operating pressure is 0.23 MPa(g) and it is associated with CCWS-1A HX. The minimum outlet operating pressure is 0.08 MPa (g) associated with Helium Compressor; while the maximum outlet

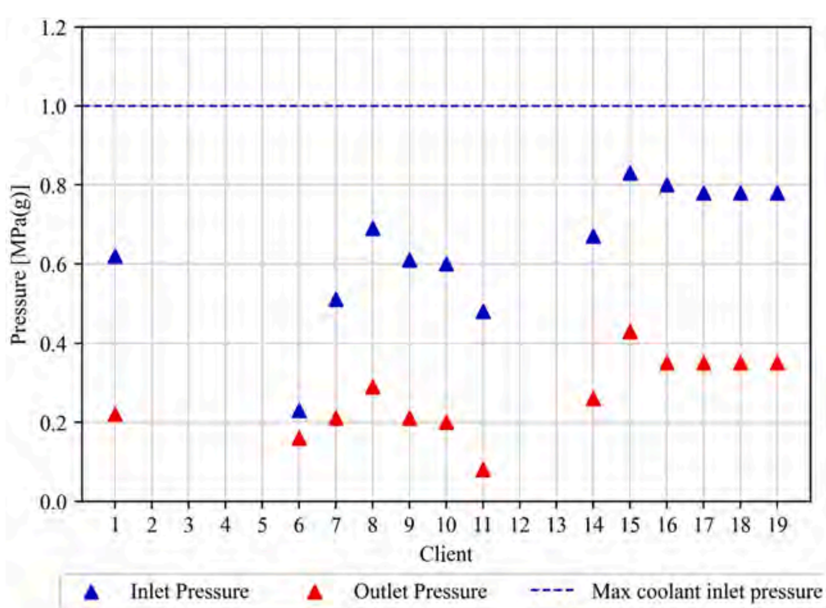

Fig. 4.8. Coolant operating pressure for clients during STM.

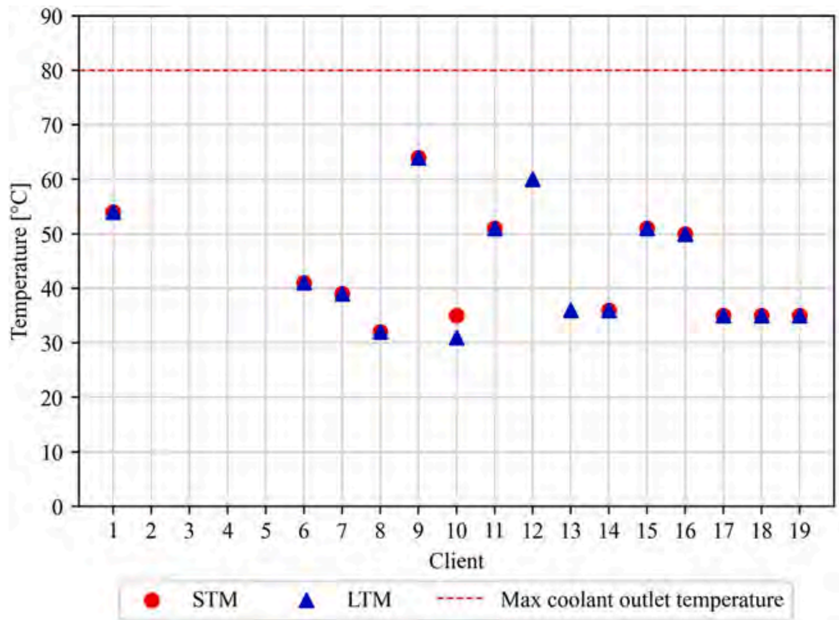

Fig. 4.9. Coolant operating outlet temperature for clients during STM and LTM.

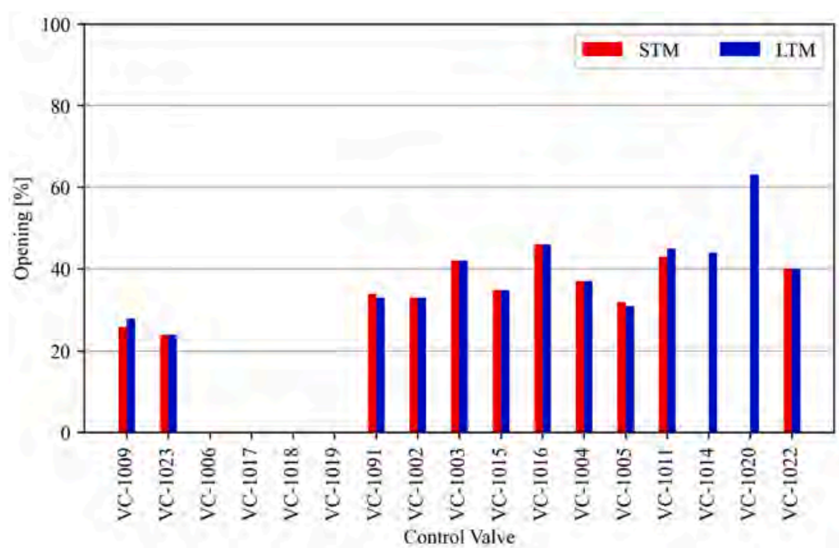

Fig. 4.10. Control valve opening percentage during STM and LTM.

operating pressure is 0.43 MPa(g) and it is associated with Electrolysers.

The distribution of coolant inlet and outlet operating pressure for each client during LTM is very similar to those presented during STM, except for the Drying System and Drying Compressor, active only during LTM, presenting an inlet coolant pressure of 0.38 MPa(g) and 0.37 MPa (g).

Fig. 4.9 presents the coolant outlet operating temperature for each client during STM and LTM. In this regard, it should be noted that the coolant inlet operating temperature for each client is 31 °C both during STM and LTM. During STM and LTM, the maximum outlet operating temperature is 64 °C associated with VV PHTS HX & Volume control. The minimum outlet operating temperature is 32 °C and it is associated with NBI PHTS HX during STM. On the other hand, during LTM, the minimum outlet operating temperature is 31 °C and it is associated with the TBM Primary Cooling System Outside the Port Cell (no heat load).

In general, during STM and LTM, the system requirements in terms of maximum coolant inlet operating temperature and pressure, maximum outlet operating temperature and maximum client pressure drop, are defined in Table 2.2.

In Fig. 4.10 the percentage of each control valve calculated by Fathom during STM and LTM is presented. All control valves present an opening percentage compatible with their selected operating range. Control valves VC-1006, VC-1017, VC-1018 and VC-1019, regulating flow rate to IBED PHTS HXs, are closed both during STM and LTM. On the other hand, the VC-1014 and VC-1020, which regulate the flow rate to the Drying System and Drying Compressor, are opened during LTM and closed during STM.

During STM, control valve VC-1016, regulating the flow rate to the Electrolysers, presents the maximum opening percentage, equal to 46 %. Then, control valve VC-1023, regulating the flow rate to the TCWS Auxiliary Cooling Header, presents the minimum open percentage, equal to 26 %.

During LTM, control valve VC-1020, regulating the flow rate to the Drying Compressor, presents the maximum opening percentage, equal to 63 %. Similar to STM conditions, control valve VC-1023 presents a minimum opening percentage, equal to 24 %.

5. Conclusion

CCWS-1 is a cooling loop of the ITER machine responsible for transferring thermal power from its clients, located inside the Tokamak Complex, to the HRS and then to the environment. In the present work, a research campaign aimed at assessing the thermal-hydraulic performance of the cooling system has been conducted to contribute to its process design. The study has been carried out using the lumped-parameters code Fathom. The first phase of the activity has been devoted to the update of the Fathom model of CCWS-1 developed by IO. Then, the activity has been focused on the verification of the proper functioning of the cooling system during the ITER operational modes: POS, TCS, STM and LTM. The pumps' operating point and PHEs heat loads to HRS have been assessed. In this regard, during the scenarios considered in the present study, the system requirements in terms of maximum coolant inlet operating temperature and pressure, maximum outlet operating temperature, maximum client pressure drop and control valve opening percentage have been respected. Moreover, the fluid velocity inside pipes has been evaluated during POS and some small portions of the circuit where fluid velocity has value outside the design velocity range have been underlined.

Disclaimer

The views and opinions expressed herein do not necessary reflect those of the ITER Organization.

CRediT authorship contribution statement

Giuseppe Agnello: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Andrea Ciampichetti:** Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **Giovanni Dell'Orco:** Supervision, Methodology. **Pietro Alessandro Di Maio:** Supervision, Methodology. **Giuseppe Di Palma:** Writing – original draft, Methodology. **Francesco Maria Farinella:** Writing – original draft, Methodology, Investigation, Conceptualization. **Sofia Maggio:** Writing – original draft, Investigation. **Eugenio Vallone:** Writing – original draft, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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In loving memory of Giovanni Dell'Orco.

Data availability

Data will be made available on request.

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